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On the latitude of the *Sq* (*H*) focus at sunspot minimum

E. C. Butcher *Division of Theoretical and Space Physics, La Trobe University, Bundoora, Victoria 3083, Australia*

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Summary. The latitude of the *Sq* (*H*) focus along the 0° longitude meridian in the northern hemisphere has been determined for all the quiet days, as determined from the aa indices, for the sunspot minimum years 1963–64–65. It is shown that: (a) most of the large variability of the focus latitude is due to the effect of a superposed northward magnetic field that is present on AQDs and which tends to move the apparent focus latitude poleward in the northern hemisphere, and (b) a smaller equatorward motion is caused by the negative AQD events that occur in the 0830–1330 LT range. When these two classes of days are removed from the data set, the focus latitude is found to be completely contained within the range 36°–48° for the months March–October with an average value of 41.5 ± 2.3, whilst in winter the range is larger with an average value of 36.7 ± 3.4. However, since the magnitude of the superposed northward field is longitude-dependent, it may be present even on days not classed as AQDs. It is shown that much of the variability in the focus latitude of the normal days along the 0° longitude meridian is caused by variations in the amplitude of the superposed northward field.

Introduction

It has been known for many years that the latitude of the *Sq* (*H*) focus varies in a more or less random manner. Although its mean position is generally accepted to be in the range 35°–40°, it may vary considerably from day to day. The source of the *Sq* (*H*) variation is known to consist of two current components. One is external to the Earth and flows mainly in the E-region of the ionosphere and this in turn induces a current to flow within the Earth. The position of the focus may be determined in one or two ways. For a series of stations spread over a sufficient latitude range along a meridian of longitude, the position of the focus may be determined at that longitude by determining the latitude where the amplitude of *Sq* (*H*) changes sign. Alternatively, for a worldwide distribution of magnetic observatories the equivalent internal and external current systems may be separately determined and a focus found for each current system. Consequently, the position of the foci may be tracked as the Earth rotates beneath the Sun. Hasegawa (1960) has made a study of the position of the *Sq* (*H*) focus for the sunspot minimum years 1932–33. Using a large number of observatories he determined the internal and external equivalent current systems and found that although there were small differences in the latitudes of the foci for the two equivalent current systems (which depended mainly on the properties of the Earth's crust and interior) they agreed to within a few degrees. For the European sector he found the mean latitude of the focus to be about 37° (geographical) for the average of the winter and summer solstice months. However, he also found that there may be considerable variability in the focus latitude over short periods of time, changes up to 15° occurring over a period of 48 hr. However, Hasegawa took no account of the phase of $Sq(H)$ on individual days nor of the effect of any possible contribution to the amplitude of $Sq(H)$ by small disturbances in H, in determining the focus latitude. Butcher & Brown (1981a) have shown that on days termed 'abnormal quiet days' (AQDs) (defined as days when the minimum in H at a mid-latitude station like Hartland on the poleward side of the focus, occurs outside the time range 0830–1330 LT), the amplitude of the normal $Sq(H)$ variation (between 0830 and 1330 LT) is significantly reduced compared to the 'normal quiet days' (NQDs) (defined as days when the minimum in H occurs between 0830–1330 LT). From an analysis of the H data on AQDs from a number of stations along the 0° meridian of longitude in the northern hemisphere, on both sides of the focus, it was found that although there was a reduction in the amplitude of $Sq(H)$ at stations on the poleward side of the focus, there was an increase in the amplitude of $Sq(H)$ on the equatorward side of the focus. This is equivalent to the addition of a superposed northward field at all latitudes along the 0° meridian on AQDs. Such an additional field therefore has the effect of shifting the apparent position of the focus (determined from the latitude at which the amplitude of $Sq(H)$ changes sign) poleward. The magnitude of this poleward movement in focus latitude was found to be significantly larger in winter than summer and was found to be dependent on the IMF polarity (Butcher & Brown 1980), it being greater on A-days (IMF away from the Sun) than on T-days (IMF towards the Sun).

The minimum in H on AQDs was found to be formed by a small negative magnetospheric substorm event (or mid-latitude bay-like disturbance, which became the minimum due to the reduction of the normal $Sq(H)$ amplitude) which occurred outside the 0830–1330 LT time range. Such substorm events may occur more or less randomly in time and when they occur within the 0830–1330 LT period they have been found to affect the amplitude and phase of the $Sq(H)$ variation (Butcher & Brown 1981b). Such events were found to be negative at all latitudes along the longitude meridian and hence had the effect of increasing the (negative) amplitude of the $Sq(H)$ variation at stations on the poleward side of the focus and of decreasing the (positive) amplitude of the $Sq(H)$ variation on the equatorward side of the focus. Hence these events which occur on days designated as quiet and which are not listed as bays in the *IAGA Bulletin* had the effect of moving the apparent position of the $Sq(H)$ focus equatorward.

It is therefore seen that in any study of the $Sq(H)$ focus position AQDs and those NQDs where a substorm event is present in the 0830–1330 LT period should be eliminated from

Table 1.

Station	Geographical coordinates		Geomagnetic coordinates	
Lerwick	60°08′N	1°11′W	60°30′N	88°36′E
Eskdalemuir	55°19′N	3°12′W	58°30′N	82°54′E
Hartland	51°0′N	4°29′W	54°36′N	79°0′E
Logrono	42°27′N	2°30′W	46°6′N	77°0′E
Toledo	39°53′N	4°3′W	43°36′N	75°42′E
Almeria	36°51′N	2°28′W	40°36′N	75°18′E
Tenerife	28°29′N	16°17′W	35°0′N	58°36′E

the analysis. The focus position then determined is most likely to be caused mainly by the ionospheric current loop responsible for *Sq* (*H*). This is particularly so in years of sunspot minimum since it is known that in this epoch the occurrence of AQDs is a maximum (Brown & Williams 1969). In this paper we have therefore considered the sunspot minimum years 1963–64–65 and determined the position of the focus along the 0° longitude meridian eliminating those days discussed above where external influences may affect the amplitude of *Sq* (*H*).

2 Selection and analysis of data

In order to determine the latitude of the *Sq* (*H*) focus in the northern hemisphere along the 0° longitude meridian hourly values of *H* from the observatories listed in Table 1 were used. It is seen that all these stations lie within a few degrees of the 0° meridian with the exception of Tenerife which is about 16° removed from the other stations. Although using data from Tenerife may introduce an error it would be expected to be too small to have much effect on the latitude of the focus determined. It is seen that such a set of stations is particularly suitable since they are favourably distributed especially near the latitude where the focus is expected to occur (i.e. near 40°) and this should allow a reasonably accurate determination. The focus was determined by plotting the maximum amplitude of the *Sq* (*H*) variation as a function of latitude and drawing a smooth curve through the points. The latitude at which this curve passsed through zero amplitude was considered to indicate the focus latitude. The maximum amplitude for each day at each station was considered as the maximum deviation from the assumed zero level of *H* given by the mean value of *H* at 0030, 0130, 2230 and 2230 LT. The maximum amplitude of *H* at each station was taken rather than the amplitude at a fixed LT (e.g. at the most probable time of maximum amplitude, 1130 LT) since it is known that there are skew effects associated with the *Sq* current system (Brown 1975).

The focal latitude was also determined for 1963 using as the zero level of *H* the mean value of *H* for that day at each station. Such a procedure naturally reduced the amplitudes determined at stations far removed from the focus latitude but made little difference at the other stations and the position of the focus was found to be within a degree or so of that using the night-time value of *H* as a zero.

Strictly speaking *Sq* (*H*) refers to the *H* variation on the five selected international quiet days in each month. Such a selection of days is therefore a relative measure of how quiet the days are magnetically. In this analysis we have determined the focus position for all those days termed quiet and given by Mayaud (1973) using the aa indices. The use of the aa indices then gives us an absolute measure of the magnetic quietness of each day. However, we are not therefore strictly measuring the position of the *Sq* (*H*) focus, but rather the S_R focus where S_R is the regular daily variation in *H* defined by Fambitakoye & Mayaud (1976). However since in the years 1963–64–65 the international quiet days are all included in the Mayaud quiet days we have referred to the focus determined on these days as the *Sq* (*H*) focus.

The focus latitude for each quiet day was determined as described above. Whether a day was classed as an AQD was determined from the hourly values of *H* at Hartland. Whether the amplitude of the variation on the remaining NQDs was affected by a (negative) magnetospheric substorm event which occurred in the 0830–1330 LT period was determined from the hourly *H*-values from the observatories listed in Table 2. The normal minima at Surlari and Sverdlovsk usually occur near 0900 UT and 0700 UT respectively and thus if a substorm event was present in the 0830–1330 UT period it should be observable in the *H* data at the two stations separate from the normal *Sq* (*H*) minimum. It has been shown elsewhere

Table 2.

Station	Geographical coordinates	
Surlari	44° 40′N	26°E
Sverdlovsk	56° 44′N	61°04′E
Meanook	54° 37′N	113°W

(Butcher 1982) that the substorm event is observed over such a range of longitude. Meanook was chosen since it had been found in a previous paper (Butcher & Brown 1981b) that on a large percentage of occasions substorm events observed at Meanook in the 0830–1330 UT time range also occurred at Hartland (The normal $Sq(H)$ minimum at Meanook occurs near 1800 UT.) Thus, if substorm events were found to be present in the H data of two of these three stations, it was assumed that the amplitude of $Sq(H)$ at the stations along the 0° longitude meridian could be affected by the substorm event. For the three years such a procedure left 234 quiet days on which a focus latitude could be determined which were considered quiet, normal days on which focus latitude was taken to represent the variation of the $Sq(H)$ focus.

3 Results

In Fig. 1 is shown the focus position for the 234 normal quiet days of 1963–64–65. It is seen that for the greater part of the year the focus is farily well behaved although there is a small seasonal shift in the latitude of the focus. It is seen to be more equatorward in the winter months (January, February, November, December) and more poleward in the summer months. This is reflected in the seasonal averages shown in Table 3 for each season, for each year separately, and (since there is little variation over the three years), for the average of the three years. The errors are the rms values and the numbers in brackets give the number of days used in determining each average.

It may be seen from this table, and Fig. 1, that there is very little difference in the latitude of the focus for the months March–October. For these eight months the average

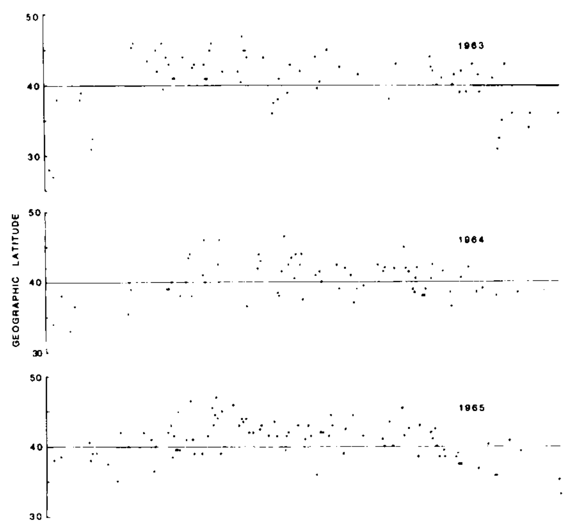

Figure 1. Focus latitude (geographical) for normal quiet days (determined from the aa indices); 1963 (top), 1964 (centre) and 1965 (bottom).

Table 3.

	JFND	MASO	MJJA
1963	35.5 ± 4.2 (18)	42.3 ± 2.9 (32)	41.9 ± 2.7 (21)
1964	36.8 ± 2.7 (9)	40.5 ± 2.2 (31)	41.4 ± 2.4 (30)
1965	37.8 ± 2.6 (19)	41.0 ± 2.4 (39)	42.3 ± 2.1 (35)
All years	36.7 ± 3.4 (46)	41.3 ± 2.4 (102)	41.9 ± 2.4 (86)

focus latitude is 42.1 ± 2.4 (53) 40.9 ± 2.3 (61) and 41.6 ± 2.3 (74) for the years 1963, 1964 and 1965 respectively and the average for all years is 41.5 ± 2.3 (188). It is seen that for these months the variability in the focus latitude is small and certainly there is none of the large changes reported by Hasegawa (1960). This may be seen more clearly from the histogram of Fig. 2. The focus is contained within a range of 12° of latitude for these months

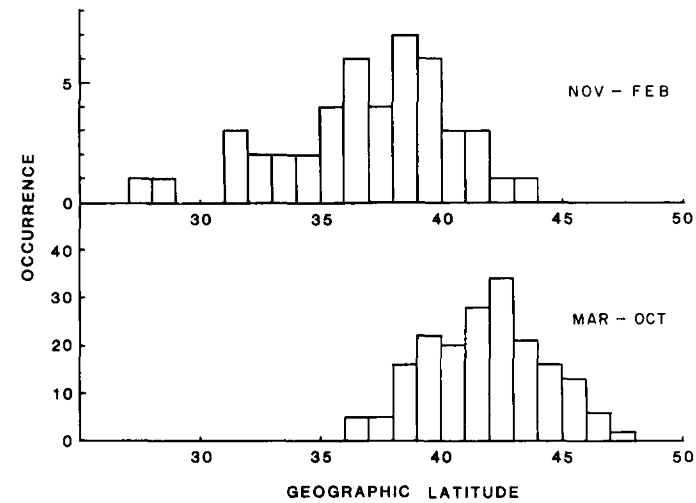

Figure 2. Histogram of the focus latitude for all normal quiet days; November–February (top), March–October (bottom).

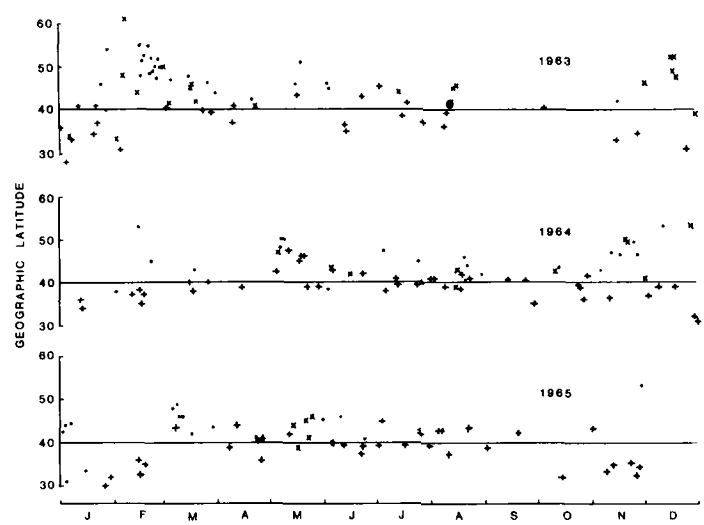

Figure 3. Focus latitude (geographical) of abnormal quiet days (AQDs) A-days (·), T-days (X), and normal quiet days where substorm event is present between 0830 and 1330 LT (+). 1963 (top), 1964 (centre) and 1965 (bottom).

and it may be seen that any real variability is confined to the winter months. If we consider only the international quiet days the focus latitude is found to be 42.0 ± 2.1, 40.8 ± 1.9 and 41.4 ± 2.8 for the months of March–October for the three years and the average latitude is found to be 41.4 ± 2.2 which is essentially the same value obtained using all the Mayaud quiet days.

In Fig. 3 is shown the focus latitude for the other quiet days during the three-year period (note that the vertical scale has been halved). The AQDs, as is well-known (Brown & Williams 1969), occur mostly in the winter and it is seen that the focus is significantly more poleward on these days, as was found previously (Butcher & Brown 1980).

For those days where a substorm event occurred in the 0830–1330 LT period and which could have affected the $Sq(H)$ amplitude, the focus latitude is seen to be mostly equatorward of the normal focus. For both these days and the AQDs the day-to-day variability in the focus latitude is seen to be greater than for the normal days shown in Fig. 1.

4 Discussion

As may be seen from Figs 1 and 2, when AQDs and the NQDs where substorm events are present during the 0830–1330 LT period are eliminated from the quiet day data, the variability in the position of the $Sq(H)$ focus of the remaining days is drastically reduced and in the months March–October the focus latitude is then completely contained within ± 6° of the most likely focus latitude. Comparison between Figs 1 and 3 shows that in particular it is the poleward motion of the focus on AQDs which contributes most to the variability of the focus position on quiet days. It is also seen, that since the focus latitude for AQDs is higher than for normal days, inclusion of AQDs in any analysis tends to make the average quiet day focus latitude high, especially in winter. In fact Hasegawa (1960) found the focus latitude in winter to be higher than that of the other seasons, a result which is not expected. In the results presented here, the focus latitude on AQDs in winter months was found to be 49.5 (28 days), 45.8 (14) and 41.5 (6) for the years 1963, 64, 65 respectively. If these days are included in with the normal quiet days and the new averages focus latitude for winter determined, it is found to be 46.0 (46), 42.3 (23) and 38.7 (25) for 1963, 64 and 65. Thus it may be seen from a comparison with the results shown in Table 3 that inclusion of the AQDs may increase the average focal latitude by up to 10°.

The additional northward field that is present on AQDs and which produces an apparent poleward motion of the focus must be caused by some redistribution of the $Sq(H)$ ionospheric currents (Butcher & Brown 1980). Either an additional west–east current flows at all latitudes over the range 14–60°N on AQDs that is not present on NQDs or an additional east–west current flows at all latitudes on NQDs that does not flow on AQDs. The magnetic effects of such currents on AQDs has been found to be dependent on both latitude and longitude (Butcher 1982) and in particular for AQDs determined from the Hartland data was found to vary smoothly with longitude falling to zero some 110° to the east of the longitude (0°) where the maximum effect occurred. Hence the amplitude of the $Sq(H)$ variation may be affected by the current flow over quite a longitude range. It is important to note, therefore, that as the magnetic effect of the current decreases, it may not be large enough to cause a day to be designated on AQD at a given longitude but the amplitude of the $Sq(H)$ variation may be significantly reduced. Thus, the focus latitude along the 0° longitude meridian on so-called normal quiet days as determined from the Hartland data may be more poleward than that due to the $Sq(H)$ current loop alone. On normal quiet days the amplitude of the $Sq(H)$ at Hartland (poleward side of focus) will be reduced and at Almeria (equatorward side of focus) it will be increased if such an additional current flow is present. (As shown previously – Butcher 1981 – the magnetic effect of such a current is

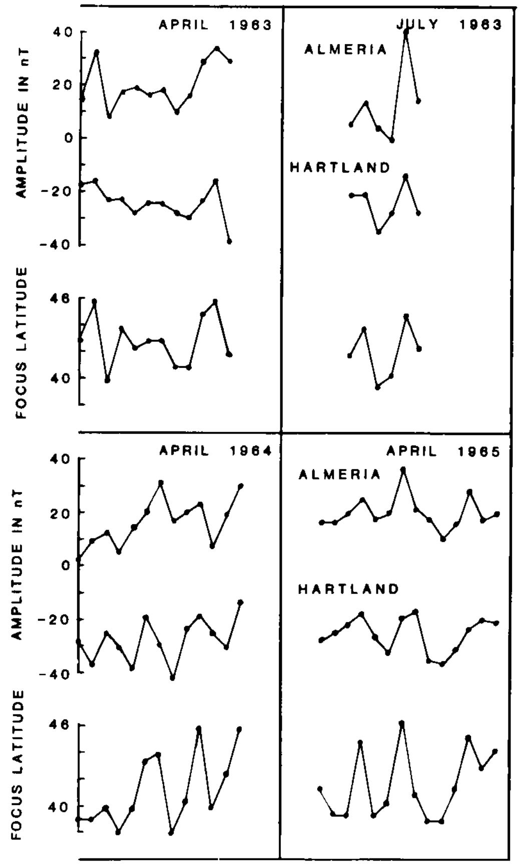

Figure 4. Amplitude of the *Sq* (*H*) variation at Almeria (top), Hartland (centre) and the focus latitude determined (bottom) for four groups of normal quiet days, i.e. excluding AQDs and substorm affected NQDs. (The days in any panel are not necessarily consecutive.)

significant at both latitudes in all seasons). Some examples are shown in Fig. 4 where there is a significant poleward motion in the apparent latitude of the focus. (The days are not necessarily consecutive.) It is seen that in such cases the changes in amplitude of *Sq* (*H*) at Hartland and Almeria are consistent with there being a variation in the additional (west–east) current flow associated with these days (rather than a change in the strength of the current in the *Sq* (*H*) current loop). Thus it would appear that much of the variability in the latitude of the focus observed in Figs 1 and 2 could be due to variations in this additional current strength along the 0° longitude meridian. Hence the mean values of the focus latitude quoted here may be taken as maximum values. Similarly, since the magnetic effect of the additional current is longitude-dependent one would also expect the focus latitude to be longitude-dependent.

The source of the current causing the additional northward magnetic field has, as yet, not been identified. Contributions to *Sq* (*H*) due to quiet time ring currents and currents flowing in the magnetotail as proposed by Olson (1974) do not have the correct latitude distributions and in any case have been shown not to be significant by Mayaud (1976). The indications are that the current flows in the ionosphere (Butcher & Brown 1981) but its driving force is unknown.

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